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Title: Software and Files Index

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Software and Files Index

The purpose of this document is to provide an index of the software and files used to generate the results and findings documented in Section 4 of the scoping study report on Radiation Signatures relevant to Thorium Fuel Cycles.

Authors and Data Owners

This data was created and compiled by (in alphabetical order):

Eric Cervi, Andrea Favalli, Vlad Henzl, Madeline Lockhart, David Mercer, and Jacob Stinnett from Safeguards Science and Technology Group (NEN-1) at Los Alamos National Laboratory.

This data is made openly available to the safeguards community for reference. Please contact Vlad Henzl (henzl@lanl.gov) regarding further use and publication of this data, for appropriate citations and any future updates to these files.

Software

GADRAS 18.8.1 – Simulation of gamma measurement, results in form of a spectrum.

Reference: GADRAS Version 18 User's Manual. Steven M. Horne, Gregory G. Thoreson, Lisa A. Theisen, Dean J. Mitchell, Lee T. Harding, and Sean E. O'Brien. SAND2019-14305

Note: For each simulation, a 1-D model was defined using parameters specified for a specific scenario as discussed in Section 4 of the "Assessment of Safeguards Technology R&D Needs for Thorium Fuel Cycles" (e.g. mass of ^{233}U, its chemical and physical form, level of ^{232}U impurities, detector type, length of measurement, etc.). Spectra were generated with the "Inject" tool using default parameters of detector response functions.

PeakEasy 4.98 – analysis of simulated or experimentally obtained gamma spectra

Reference: Rooney, B., Garner, S., Felsher, P., Karpius, P., (2018), PeakEasy 4.98 [Computer Program], Los Alamos National Laboratory, Release LA-CC-13-040, https://PeakEasy.lanl.gov.

DeCayculator: - calculation of activities of ^{233}U and ^{232}U decay chains products

Reference: P. Karpius. The DeCayculator, Beta Version 1.0., Los Alamos National Laboratory, LA-CC-11-82; ICRP, 1983. Radionuclide Transformations - Energy and Intensity of Emissions. ICRP Publication 38. Ann. ICRP 11-13.

Note: LANL-internal code to compute activities of ^{233}U and ^{232}U decay chain products over time, based on ICRP 38 nuclear data. This calculated activities over time for then served as input for to calculate dose rates over time.

Files

Reports documents:

- **DoseCalculations.xlsx:** Contains data used for activity and dose over time figures. Activity data generated with Decayculator, and dose rate information is from PeakEasy. See Appendix A.
- **Files and Software Index.docx:** this file
- **RefData.xlsx:** reference data for uranium and thorium, such as half-lives, specific power (for calorimetry), spontaneous fission rates, etc.. See Appendix B
- **ThoriumMeasurements.**xlsx: compilation of neutron rates (S, D, T) measured with AWCC and ENMC detector during assay of various ^{252}Cf, Pu and Th and items. See Appendix C

GADRAS files

- **Thorium.pcf**: a GADRAS-generated spectra file with four spectra inside, numbered 1-4 (note: file generically named "Thorium" as it was created for the Th-safeguards project, however it contains all relevant spectra, some only with ^{233}U). See Appendix D
    1. Uses the ThoriumBall.1dm model
    2. Uses the ThoriumBall.1dm model
    3. Uses the U233Ball.1dm model
    4. Uses the U233Ball.1dm model
- **ThoriumBall.1dm**: a GADRAS 1-D model file of a 1 kg thorium oxide item. See Appendix E
- **U233.1dm**: a GADRAS 1-D model file of a 10-gram U-233 metal item. See Appendix E
- **ThoriumBall.gam**: a GADRAS gamma file; contains the physics data generated by the associated 1-D mode. See Appendix F
- **U233Ball.gam**: a GADRAS gamma file; contains the physics data generated by the associated 1-D model. See Appendix F.

Appendix A: DoseCalculations.xlsx

General item properties:

Total U Mass [g]	1.00
^{232}U contamination [ppm]	10.0

Item properties by isotope:

Nuclide	[wt%]	Activity [s^{-1}]	Activity [%]
^{232}U	0.001	2.24E-02	2.25
^{233}U	99.999	0.9699903	97.75

Raw Decayculator Results - ^{233}U decay

Nuclide	Age [y] 0.00274	0.02	0.1	0.25	0.5	0.75	1	1.5	2	2.5	3	4	5	6	7	8	9	10	12.5	15	17.5	20	25	50	100
^{233}U	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00
^{229}Th	2.59E-07	1.89E-06	9.44E-06	2.36E-05	4.72E-05	7.08E-05	9.44E-05	1.42E-04	1.89E-04	2.36E-04	2.83E-04	3.78E-04	4.72E-04	5.66E-04	6.61E-04	7.55E-04	8.50E-04	9.44E-04	1.18E-03	1.42E-03	1.65E-03	1.89E-03	2.36E-03	4.71E-03	9.40E-03
^{225}Ra	5.97E-09	2.89E-07	4.92E-06	1.82E-05	4.17E-05	6.53E-05	8.89E-05	1.36E-04	1.83E-04	2.31E-04	2.78E-04	3.72E-04	4.67E-04	5.61E-04	6.55E-04	7.50E-04	8.44E-04	9.38E-04	1.17E-03	1.41E-03	1.65E-03	1.88E-03	2.35E-03	4.71E-03	9.39E-03
^{225}Ac	1.36E-10	4.43E-08	2.65E-06	1.46E-05	3.80E-05	6.16E-05	8.52E-05	1.32E-04	1.80E-04	2.27E-04	2.74E-04	3.68E-04	4.63E-04	5.57E-04	6.52E-04	7.46E-04	8.40E-04	9.35E-04	1.17E-03	1.41E-03	1.64E-03	1.88E-03	2.35E-03	4.70E-03	9.39E-03
^{221}Fr	1.34E-10	4.42E-08	2.65E-06	1.46E-05	3.80E-05	6.16E-05	8.52E-05	1.32E-04	1.80E-04	2.27E-04	2.74E-04	3.68E-04	4.63E-04	5.57E-04	6.52E-04	7.46E-04	8.40E-04	9.35E-04	1.17E-03	1.41E-03	1.64E-03	1.88E-03	2.35E-03	4.70E-03	9.39E-03
^{217}At	1.34E-10	4.42E-08	2.65E-06	1.46E-05	3.80E-05	6.16E-05	8.52E-05	1.32E-04	1.80E-04	2.27E-04	2.74E-04	3.68E-04	4.63E-04	5.57E-04	6.52E-04	7.46E-04	8.40E-04	9.35E-04	1.17E-03	1.41E-03	1.64E-03	1.88E-03	2.35E-03	4.70E-03	9.39E-03
^{213}Bi	1.18E-10	4.35E-08	2.64E-06	1.46E-05	3.80E-05	6.16E-05	8.52E-05	1.32E-04	1.80E-04	2.27E-04	2.74E-04	3.68E-04	4.63E-04	5.57E-04	6.52E-04	7.46E-04	8.40E-04	9.35E-04	1.17E-03	1.41E-03	1.64E-03	1.88E-03	2.35E-03	4.70E-03	9.39E-03
^{213}Po	1.15E-10	4.25E-08	2.59E-06	1.43E-05	3.71E-05	6.02E-05	8.33E-05	1.30E-04	1.76E-04	2.22E-04	2.68E-04	3.60E-04	4.53E-04	5.45E-04	6.38E-04	7.30E-04	8.22E-04	9.14E-04	1.15E-03	1.38E-03	1.61E-03	1.84E-03	2.30E-03	4.60E-03	9.19E-03
^{209}Tl	2.52E-12	9.38E-10	5.71E-08	3.15E-07	8.20E-07	1.33E-06	1.84E-06	2.86E-06	3.88E-06	4.90E-06	5.92E-06	7.96E-06	1.00E-05	1.20E-05	1.41E-05	1.61E-05	1.82E-05	2.02E-05	2.53E-05	3.04E-05	3.55E-05	4.06E-05	5.07E-05	1.02E-04	2.03E-04
^{209}Pb	6.91E-11	4.03E-08	2.61E-06	1.45E-05	3.79E-05	6.15E-05	8.51E-05	1.32E-04	1.80E-04	2.27E-04	2.74E-04	3.68E-04	4.63E-04	5.57E-04	6.52E-04	7.46E-04	8.40E-04	9.35E-04	1.17E-03	1.41E-03	1.64E-03	1.88E-03	2.35E-03	4.70E-03	9.39E-03

Raw Decayculator Results- ^{232}U decay

Nuclide	Age [y] 0.00274	0.02	0.1	0.25	0.5	0.75	1	1.5	2	2.5	3	4	5	6	7	8	9	10	12.5	15	17.5	20	25	50	100
^{232}U	1.00E+00	1.00E+00	9.99E-01	9.98E-01	9.95E-01	9.93E-01	9.90E-01	9.86E-01	9.81E-01	9.76E-01	9.72E-01	9.62E-01	9.53E-01	9.44E-01	9.35E-01	9.26E-01	9.17E-01	9.08E-01	8.87E-01	8.66E-01	8.45E-01	8.25E-01	7.86E-01	6.18E-01	3.82E-01
^{228}Th	9.92E-04	7.22E-03	3.56E-02	8.65E-02	1.65E-01	2.37E-01	3.02E-01	4.16E-01	5.10E-01	5.88E-01	6.52E-01	7.47E-01	8.11E-01	8.53E-01	8.79E-01	8.95E-01	9.03E-01	9.06E-01	9.00E-01	8.85E-01	8.66E-01	8.47E-01	8.07E-01	6.35E-01	3.92E-01
^{224}Ra	8.84E-05	3.31E-03	3.05E-02	8.17E-02	1.61E-01	2.33E-01	2.99E-01	4.13E-01	5.08E-01	5.86E-01	6.50E-01	7.46E-01	8.10E-01	8.52E-01	8.79E-01	8.94E-01	9.03E-01	9.06E-01	9.00E-01	8.85E-01	8.66E-01	8.47E-01	8.08E-01	6.35E-01	3.92E-01
^{220}Rn	8.82E-05	3.31E-03	3.05E-02	8.17E-02	1.61E-01	2.33E-01	2.99E-01	4.13E-01	5.08E-01	5.86E-01	6.50E-01	7.46E-01	8.10E-01	8.52E-01	8.79E-01	8.94E-01	9.03E-01	9.06E-01	9.00E-01	8.85E-01	8.66E-01	8.47E-01	8.08E-01	6.35E-01	3.92E-01
^{216}Po	8.82E-05	3.31E-03	3.05E-02	8.17E-02	1.61E-01	2.33E-01	2.99E-01	4.13E-01	5.08E-01	5.86E-01	6.50E-01	7.46E-01	8.10E-01	8.52E-01	8.79E-01	8.94E-01	9.03E-01	9.06E-01	9.00E-01	8.85E-01	8.66E-01	8.47E-01	8.08E-01	6.35E-01	3.92E-01
^{212}Pb	3.28E-05	2.86E-03	2.99E-02	8.11E-02	1.60E-01	2.33E-01	2.98E-01	4.13E-01	5.07E-01	5.85E-01	6.50E-01	7.46E-01	8.10E-01	8.52E-01	8.79E-01	8.94E-01	9.03E-01	9.06E-01	9.00E-01	8.85E-01	8.66E-01	8.47E-01	8.08E-01	6.35E-01	3.92E-01
^{212}Bi	2.81E-05	2.82E-03	2.98E-02	8.11E-02	1.60E-01	2.33E-01	2.98E-01	4.13E-01	5.07E-01	5.85E-01	6.50E-01	7.46E-01	8.10E-01	8.52E-01	8.79E-01	8.94E-01	9.03E-01	9.06E-01	9.00E-01	8.85E-01	8.66E-01	8.47E-01	8.08E-01	6.35E-01	3.92E-01
^{212}Po	1.80E-05	1.81E-03	1.91E-02	5.19E-02	1.03E-01	1.49E-01	1.91E-01	2.64E-01	3.25E-01	3.75E-01	4.16E-01	4.78E-01	5.19E-01	5.46E-01	5.63E-01	5.73E-01	5.78E-01	5.80E-01	5.77E-01	5.67E-01	5.55E-01	5.43E-01	5.17E-01	4.07E-01	2.51E-01
^{208}Tl	9.99E-06	1.01E-03	1.07E-02	2.91E-02	5.76E-02	8.36E-02	1.07E-01	1.48E-01	1.82E-01	2.10E-01	2.33E-01	2.68E-01	2.91E-01	3.06E-01	3.16E-01	3.21E-01	3.24E-01	3.25E-01	3.23E-01	3.18E-01	3.11E-01	3.04E-01	2.90E-01	2.28E-01	1.41E-01

Activity (Ci) vs time

Nuclide	Age [y] 0.00274	0.02	0.1	0.25	0.5	0.75	1	1.5	2	2.5	3	4	5	6	7	8	9	10	12.5	15	17.5	20	25	50	100
^{233}U	9.70E-01	9.70E-01	9.70E-01	9.70E-01	9.70E-01	9.70E-01	9.70E-01	9.70E-01	9.70E-01	9.70E-01	9.70E-01	9.70E-01	9.70E-01	9.70E-01	9.70E-01	9.70E-01	9.70E-01	9.70E-01	9.70E-01	9.70E-01	9.70E-01	9.70E-01	9.70E-01	9.70E-01	9.70E-01
^{229}Th	2.51E-07	1.83E-06	9.16E-06	2.29E-05	4.58E-05	6.87E-05	9.16E-05	1.37E-04	1.83E-04	2.29E-04	2.75E-04	3.66E-04	4.58E-04	5.49E-04	6.41E-04	7.33E-04	8.24E-04	9.16E-04	1.14E-03	1.37E-03	1.60E-03	1.83E-03	2.29E-03	4.57E-03	9.11E-03
^{225}Ra	5.79E-09	2.81E-07	4.77E-06	1.76E-05	4.04E-05	6.33E-05	8.62E-05	1.32E-04	1.78E-04	2.24E-04	2.69E-04	3.61E-04	4.53E-04	5.44E-04	6.36E-04	7.27E-04	8.19E-04	9.10E-04	1.14E-03	1.37E-03	1.60E-03	1.82E-03	2.28E-03	4.56E-03	9.11E-03
^{225}Ac	1.32E-10	4.30E-08	2.57E-06	1.41E-05	3.68E-05	5.97E-05	8.26E-05	1.28E-04	1.74E-04	2.20E-04	2.66E-04	3.57E-04	4.49E-04	5.40E-04	6.32E-04	7.24E-04	8.15E-04	9.07E-04	1.13E-03	1.36E-03	1.59E-03	1.82E-03	2.28E-03	4.56E-03	9.11E-03
^{221}Fr	1.30E-10	4.29E-08	2.57E-06	1.41E-05	3.68E-05	5.97E-05	8.26E-05	1.28E-04	1.74E-04	2.20E-04	2.66E-04	3.57E-04	4.49E-04	5.40E-04	6.32E-04	7.24E-04	8.15E-04	9.07E-04	1.13E-03	1.36E-03	1.59E-03	1.82E-03	2.28E-03	4.56E-03	9.11E-03
^{217}At	1.30E-10	4.29E-08	2.57E-06	1.41E-05	3.68E-05	5.97E-05	8.26E-05	1.28E-04	1.74E-04	2.20E-04	2.66E-04	3.57E-04	4.49E-04	5.40E-04	6.32E-04	7.24E-04	8.15E-04	9.07E-04	1.13E-03	1.36E-03	1.59E-03	1.82E-03	2.28E-03	4.56E-03	9.11E-03
^{213}Bi	1.14E-10	4.22E-08	2.56E-06	1.41E-05	3.68E-05	5.97E-05	8.26E-05	1.28E-04	1.74E-04	2.20E-04	2.66E-04	3.57E-04	4.49E-04	5.40E-04	6.32E-04	7.24E-04	8.15E-04	9.07E-04	1.13E-03	1.36E-03	1.59E-03	1.82E-03	2.28E-03	4.56E-03	9.11E-03
^{213}Po	1.12E-10	4.13E-08	2.51E-06	1.38E-05	3.60E-05	5.84E-05	8.08E-05	1.26E-04	1.70E-04	2.15E-04	2.60E-04	3.50E-04	4.39E-04	5.29E-04	6.18E-04	7.08E-04	7.97E-04	8.87E-04	1.11E-03	1.33E-03	1.56E-03	1.78E-03	2.23E-03	4.46E-03	8.91E-03
^{209}Tl	2.45E-12	9.10E-10	5.54E-08	3.05E-07	7.95E-07	1.29E-06	1.78E-06	2.77E-06	3.76E-06	4.75E-06	5.74E-06	7.72E-06	9.70E-06	1.17E-05	1.36E-05	1.56E-05	1.76E-05	1.96E-05	2.45E-05	2.95E-05	3.44E-05	3.93E-05	4.92E-05	9.85E-05	1.97E-04
^{209}Pb	6.70E-11	3.91E-08	2.53E-06	1.41E-05	3.68E-05	5.97E-05	8.26E-05	1.28E-04	1.74E-04	2.20E-04	2.66E-04	3.57E-04	4.49E-04	5.40E-04	6.32E-04	7.24E-04	8.15E-04	9.07E-04	1.13E-03	1.36E-03	1.59E-03	1.82E-03	2.28E-03	4.56E-03	9.11E-03
^{233}U	2.24E-02	2.24E-02	2.23E-02	2.23E-02	2.23E-02	2.22E-02	2.21E-02	2.20E-02	2.20E-02	2.19E-02	2.18E-02	2.17E-02	2.15E-02	2.13E-02	2.11E-02	2.09E-02	2.07E-02	2.05E-02	2.03E-02	1.98E-02	1.94E-02	1.89E-02	1.84E-02	1.76E-02	1.38E-02	8.54E-03
^{228}Th	2.22E-05	1.61E-04	7.95E-04	1.93E-03	3.70E-03	5.30E-03	6.76E-03	9.30E-03	1.14E-02	1.31E-02	1.46E-02	1.67E-02	1.81E-02	1.91E-02	1.97E-02	2.00E-02	2.02E-02	2.02E-02	2.01E-02	1.98E-02	1.94E-02	1.89E-02	1.81E-02	1.42E-02	8.77E-03
^{224}Ra	1.98E-06	7.41E-05	6.82E-04	1.83E-03	3.60E-03	5.21E-03	6.68E-03	9.23E-03	1.13E-02	1.31E-02	1.45E-02	1.67E-02	1.81E-02	1.91E-02	1.96E-02	2.00E-02	2.02E-02	2.02E-02	2.01E-02	1.98E-02	1.94E-02	1.89E-02	1.81E-02	1.42E-02	8.77E-03
^{220}Rn	1.97E-06	7.41E-05	6.82E-04	1.83E-03	3.60E-03	5.21E-03	6.68E-03	9.23E-03	1.13E-02	1.31E-02	1.45E-02	1.67E-02	1.81E-02	1.91E-02	1.96E-02	2.00E-02	2.02E-02	2.02E-02	2.01E-02	1.98E-02	1.94E-02	1.89E-02	1.81E-02	1.42E-02	8.77E-03
^{216}Po	1.97E-06	7.41E-05	6.82E-04	1.83E-03	3.60E-03	5.21E-03	6.68E-03	9.23E-03	1.13E-02	1.31E-02	1.45E-02	1.67E-02	1.81E-02	1.91E-02	1.96E-02	2.00E-02	2.02E-02	2.02E-02	2.01E-02	1.98E-02	1.94E-02	1.89E-02	1.81E-02	1.42E-02	8.77E-03
^{212}Pb	7.34E-07	6.39E-05	6.68E-04	1.81E-03	3.59E-03	5.20E-03	6.67E-03	9.23E-03	1.13E-02	1.31E-02	1.45E-02	1.67E-02	1.81E-02	1.91E-02	1.96E-02	2.00E-02	2.02E-02	2.02E-02	2.01E-02	1.98E-02	1.94E-02	1.89E-02	1.81E-02	1.42E-02	8.77E-03
^{212}Bi	6.27E-07	6.30E-05	6.67E-04	1.81E-03	3.58E-03	5.20E-03	6.67E-03	9.23E-03	1.13E-02	1.31E-02	1.45E-02	1.67E-02	1.81E-02	1.91E-02	1.96E-02	2.00E-02	2.02E-02	2.02E-02	2.01E-02	1.98E-02	1.94E-02	1.89E-02	1.81E-02	1.42E-02	8.77E-03
^{212}Po	4.02E-07	4.04E-05	4.27E-04	1.16E-03	2.30E-03	3.33E-03	4.27E-03	5.91E-03	7.27E-03	8.39E-03	9.31E-03	1.07E-02	1.16E-02	1.22E-02	1.26E-02	1.28E-02	1.29E-02	1.30E-02	1.29E-02	1.27E-02	1.24E-02	1.21E-02	1.16E-02	9.10E-03	5.62E-03
^{208}Tl	2.23E-07	2.26E-05	2.40E-04	6.51E-04	1.29E-03	1.87E-03	2.40E-03	3.31E-03	4.07E-03	4.70E-03	5.22E-03	5.99E-03	6.51E-03	6.85E-03	7.06E-03	7.18E-03	7.25E-03	7.28E-03	7.23E-03	7.11E-03	6.96E-03	6.80E-03	6.49E-03	5.10E-03	3.15E-03

Gamma Dose (Rem/hr@1m) vs time

Nuclide	Age [y] 0.00274	0.02	0.1	0.25	0.5	0.75	1	1.5	2	2.5	3	4	5	6	7	8	9	10	12.5	15	17.5	20	25	50	100
^{233}U	2.52E-04	2.52E-04	2.52E-04	2.52E-04	2.52E-04	2.52E-04	2.52E-04	2.52E-04	2.52E-04	2.52E-04	2.52E-04	2.52E-04	2.52E-04	2.52E-04	2.52E-04	2.52E-04	2.52E-04	2.52E-04	2.52E-04	2.52E-04	2.52E-04	2.52E-04	2.52E-04	2.52E-04	2.52E-04
^{229}Th	8.11E-09	5.92E-08	2.96E-07	7.40E-07	1.48E-06	2.22E-06	2.96E-06	4.44E-06	5.92E-06	7.40E-06	8.88E-06	1.18E-05	1.48E-05	1.77E-05	2.07E-05	2.37E-05	2.66E-05	2.96E-05	3.70E-05	4.43E-05	5.17E-05	5.91E-05	7.39E-05	1.48E-04	2.94E-04
^{225}Ra	1.84E-10	8.92E-09	1.52E-07	5.60E-07	1.29E-06	2.01E-06	2.74E-06	4.20E-06	5.65E-06	7.11E-06	8.57E-06	1.15E-05	1.44E-05	1.73E-05	2.02E-05	2.31E-05	2.60E-05	2.89E-05	3.62E-05	4.35E-05	5.08E-05	5.80E-05	7.25E-05	1.45E-04	2.90E-04
^{225}Ac	1.08E-12	3.53E-10	2.11E-08	1.16E-07	3.02E-07	4.90E-07	6.78E-07	1.05E-06	1.43E-06	1.80E-06	2.18E-06	2.93E-06	3.68E-06	4.43E-06	5.18E-06	5.93E-06	6.68E-06	7.43E-06	9.31E-06	1.12E-05	1.31E-05	1.49E-05	1.87E-05	3.74E-05	7.47E-05
^{221}Fr	5.75E-12	1.89E-09	1.14E-07	6.24E-07	1.63E-06	2.64E-06	3.65E-06	5.67E-06	7.69E-06	9.71E-06	1.17E-05	1.58E-05	1.98E-05	2.39E-05	2.79E-05	3.19E-05	3.60E-05	4.00E-05	5.01E-05	6.02E-05	7.03E-05	8.04E-05	1.01E-04	2.01E-04	4.02E-04
^{217}At	2.09E-14	6.88E-12	4.12E-10	2.27E-09	5.90E-09	9.57E-09	1.32E-08	2.06E-08	2.79E-08	3.53E-08	4.26E-08	5.73E-08	7.19E-08	8.66E-08	1.01E-07	1.16E-07	1.31E-07	1.45E-07	1.82E-07	2.19E-07	2.55E-07	2.92E-07	3.65E-07	7.31E-07	1.46E-06
^{213}Bi	9.94E-12	3.68E-09	2.24E-07	1.23E-06	3.21E-06	5.21E-06	7.20E-06	1.12E-05	1.52E-05	1.92E-05	2.32E-05	3.12E-05	3.91E-05	4.71E-05	5.51E-05	6.31E-05	7.11E-05	7.91E-05	9.90E-05	1.19E-04	1.39E-04	1.59E-04	1.99E-04	3.98E-04	7.94E-04
^{213}Po	2.16E-15	8.00E-13	4.87E-11	2.68E-10	6.99E-10	1.13E-09	1.57E-09	2.44E-09	3.31E-09	4.18E-09	5.05E-09	6.78E-09	8.52E-09	1.03E-08	1.20E-08	1.37E-08	1.55E-08	1.72E-08	2.15E-08	2.59E-08	3.02E-08	3.46E-08	4.32E-08	8.65E-08	1.73E-07
^{209}Tl	3.16E-12	1.18E-09	7.16E-08	3.95E-07	1.03E-06	1.67E-06	2.31E-06	3.59E-06	4.87E-06	6.15E-06	7.43E-06	9.98E-06	1.25E-05	1.51E-05	1.77E-05	2.02E-05	2.28E-05	2.53E-05	3.17E-05	3.81E-05	4.45E-05	5.09E-05	6.37E-05	1.27E-04	2.54E-04
^{209}Pb	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
^{232}U	5.37E-06	5.37E-06	5.36E-06	5.35E-06	5.34E-06	5.33E-06	5.31E-06	5.29E-06	5.26E-06	5.24E-06	5.21E-06	5.16E-06	5.11E-06	5.07E-06	5.02E-06	4.97E-06	4.92E-06	4.87E-06	4.76E-06	4.64E-06	4.53E-06	4.43E-06	4.22E-06	3.32E-06	2.05E-06
^{228}Th	3.64E-08	2.65E-07	1.30E-06	3.17E-06	6.06E-06	8.69E-06	1.11E-05	1.53E-05	1.87E-05	2.15E-05	2.39E-05	2.74E-05	2.97E-05	3.13E-05	3.22E-05	3.28E-05	3.31E-05	3.32E-05	3.30E-05	3.24E-05	3.18E-05	3.10E-05	2.96E-05	2.33E-05	1.44E-05
^{224}Ra	1.46E-08	5.47E-07	5.04E-06	1.35E-05	2.66E-05	3.85E-05	4.94E-05	6.82E-05	8.39E-05	9.68E-05	1.07E-04	1.23E-04	1.34E-04	1.41E-04	1.45E-04	1.48E-04	1.49E-04	1.50E-04	1.49E-04	1.46E-04	1.43E-04	1.40E-04	1.33E-04	1.05E-04	6.48E-05
^{220}Rn	8.48E-10	3.18E-08	2.93E-07	7.86E-07	1.55E-06	2.24E-06	2.87E-06	3.97E-06	4.88E-06	5.63E-06	6.25E-06	7.17E-06	7.79E-06	8.19E-06	8.45E-06	8.60E-06	8.68E-06	8.71E-06	8.65E-06	8.51E-06	8.33E-06	8.14E-06	7.76E-06	6.10E-06	3.77E-06
^{216}Po	1.77E-11	6.64E-10	6.12E-09	1.64E-08	3.23E-08	4.67E-08	5.99E-08	8.28E-08	1.02E-07	1.17E-07	1.30E-07	1.50E-07	1.63E-07	1.71E-07	1.76E-07	1.79E-07	1.81E-07	1.82E-07	1.80E-07	1.77E-07	1.74E-07	1.70E-07	1.62E-07	1.27E-07	7.87E-08
^{212}Pb	2.01E-07	1.75E-05	1.83E-04	4.96E-04	9.81E-04	1.42E-03	1.82E-03	2.52E-03	3.10E-03	3.58E-03	3.97E-03	4.56E-03	4.95E-03	5.21E-03	5.37E-03	5.47E-03	5.52E-03	5.54E-03	5.50E-03	5.41E-03	5.30E-03	5.18E-03	4.94E-03	3.88E-03	2.40E-03
^{212}Bi	3.86E-08	3.88E-06	4.10E-05	1.11E-04	2.20E-04	3.20E-04	4.10E-04	5.67E-04	6.97E-04	8.05E-04	8.93E-04	1.03E-03	1.11E-03	1.17E-03	1.21E-03	1.23E-03	1.24E-03	1.25E-03	1.24E-03	1.22E-03	1.19E-03	1.16E-03	1.11E-03	8.73E-04	5.39E-04
^{212}Po	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
^{208}Tl	3.64E-07	3.69E-05	3.91E-04	1.06E-03	2.10E-03	3.05E-03	3.91E-03	5.40E-03	6.64E-03	7.66E-03	8.51E-03	9.77E-03	1.06E-02	1.12E-02	1.15E-02	1.17E-02	1.18E-02	1.19E-02	1.18E-02	1.16E-02	1.13E-02	1.11E-02	1.06E-02	8.31E-03	5.14E-03
Total	**2.58E-04**	**3.17E-04**	**8.79E-04**	**1.95E-03**	**3.60E-03**	**5.11E-03**	**6.48E-03**	**8.87E-03**	**1.08E-02**	**1.25E-02**	**1.38E-02**	**1.59E-02**	**1.72E-02**	**1.81E-02**	**1.87E-02**	**1.90E-02**	**1.92E-02**	**1.93E-02**	**1.92E-02**	**1.90E-02**	**1.86E-02**	**1.83E-02**	**1.76E-02**	**1.45E-02**	**1.05E-02**

Nuclide	Gamma Dose [Rem/hr@1m/Ci] [*]	Specific Activity [Ci/g]	Primary Decay Mode	Atomic weight	Alpha energy [keV] [**]	Beta endpoint E [keV] [**]
^{233}U	2.60E-04	0.0097	α	233	4908	-
^{229}Th	3.23E-02	0.2126	α	229	5167	-
^{225}Ra	3.18E-02	3.92E+04	β$^-$	225	-	357
^{225}Ac	8.20E-03	5.80E+04	α	225	5935.1	-
^{221}Fr	4.41E-02		α	221	6458.1	-
^{217}At	1.60E-04		99.99% α	217	7201.9	-
^{213}Bi	8.72E-02	1.93E+07		213	5982	-
^{213}Po	1.94E-05	1.26E+16	α	213	8537	-
^{209}Tl	1.29E+00	4.09E+08	β$^-$	209	-	3980
^{209}Pb				209	-	-
^{232}U	0.00024	2.24E+01	α	232	5413.55	-
^{228}Th	0.00164	8.25E+02	α	228	5520.12	-
^{224}Ra	0.00739	1.59E+05	α	224	5788.87	-
^{220}Rn	0.00043	9.22E+08	α	220	6404.67	-
^{216}Po	8.97E-06		α	216	6906.5	-
^{212}Pb	0.273393		β$^-$	212	-	573.7
^{212}Bi	0.0615	1.46E+07	64.06%beta, 35.94% α	212	6207.14	2254
^{212}Po		1.80E+17	α	212	8954.13	-
^{208}Tl	1.63	2.92E+08	β$^-$	208	-	5000.9

[*] from PeakEasy
[**] http://nucleardata.nuclear.lu.se/toi/abouttoi.htm

Appendix B: RefData.xlsx

Nuclide	Half life	Primary Decay Mode	Spontaneous Fission Rate - SF [$s^{-1} \cdot kg^{-1}$]	Fission Cross Section - σ [b]; fission spectrum avg	SF Neutron Multiplicity - nu_{SF} [1]	Fission Spectrum Neutron Multiplicity - nu_{FS} [1]	Critical Mass - M_c [kg]	Decay Heat - Q [W/kg]	Specific Activity [Ci/kg]
^{232}Th	1.405 x 10^{10} y	Alpha 4.083 MeV	<5 x 10^{-5}	0.0785	-	2.16	None	2.654 x 10^{-6}	1.097 x 10^{-4}
^{231}Pa	32760 y	Alpha 5.149 MeV	<5	0.834	-	2.457	>188	1.442	47.23
^{232}U	68.9 y	Alpha 5.414 MeV	2 x 10^{-3}	2.013	2	3.296	>5	717.6	22,360
^{233}U	159200 y	Alpha 4.909 MeV	-	1.946	-	2.649	16	0.2804	9.636
^{234}U	245500 y	Alpha 4.859 MeV	3.9	1.223	1.8	2.578	>41	0.1792	6.222
^{235}U	7.038 x 10^{8} y	Alpha 4.679 MeV	5.6 x 10^{-3}	1.235	2	2.6055	48	5.994 x 10^{-5}	2.161 x 10^{-3}
^{236}U	2.342 x 10^{7} y	Alpha 4.572 MeV	2.3	0.594	1.8	2.526	>167	1.753 x 10^{-3}	0.06467
^{238}U	4.468 x 10^{9} y	Alpha 4.270 MeV	5.51	0.308	1.97 ± 0.07	2.601	None	8.508 x 10^{-6}	3.361 x 10^{-4}
^{237}Np	2.144 x 10^{6} y	Alpha 4.959 MeV	< 0.05	1.335	2	2.889	75-105	0.02068	0.7034
^{238}Pu	87.7 y	Alpha 5.593 MeV	1.204 x 10^{6}	1.994	2.28 ± 0.10	3.148	9	5.678 x 10^{5}	17,120
^{239}Pu	24110 y	Alpha 5.245 MeV	10.1	1.8	2.9	3.1231	10.5	1.929	62.03
^{240}Pu	65640 y	Alpha 5.256 MeV	478,000	1.357	2.189 ± 0.026	3.061	40	7.07	227
^{241}Pu	14.35 y	Beta 0.021 MeV	<0.8	1.648	-	3.142	12	129.4	1.033 x 10^{5}
^{242}Pu	373300 y	Alpha 4.984 MeV	805,000	1.127	2.28 ± 0.13	3.07	95, range 75-100	0.1169	3.956
^{241}Am	432.2 y	Alpha 5.638 MeV	500	1.378	2	3.457	83.5	114.7	3,431
^{251}Cf	898 y	Alpha 6.176 MeV	-	2.43	-	4.56	1.94	58.05	1,586

Appendix C: ThoriumMeasurements.xlsx

ACTIVE Measurements

AWCC — **No Cd liner, No Ni** — **8/21/2019** — *Note: ^{252}Cf in bottom plug, ^{232}Th on 7 cm stand in cavity*

Items	Measurement time	^{232}Th mass [g]	Singles	σ	Doubles	σ	Triples	σ	Δ Singles	σ	Δ Doubles	σ	Δ Triples	σ
bkg	60 x 20s = 20 min	0	21.62	0.34	0.345	0.025	0.027	0.006	-	-	-	-	-	-
FTC-CF-1992	60 x 20s = 20 min	0	47466.8	7.2	4256.3	10.6	232.0	17.9	-	-	-	-	-	-
FTC-CF-1992, TH-5D	90 x 20s = 30 min	31.5	47351.1	5.2	4231.9	10.2	232.8	14.3	-115.75	8.86	-24.37	14.75	0.84	22.92
FTC-CF-1992, TH-5D, TH-6D	90 x 20s = 30 min	59.5	47406.1	5.2	4256.7	10.0	208.2	12.7	-60.75	8.86	0.43	14.60	-23.79	21.96
FTC-CF-1992, TH-5D, TH-6D, TH-9D, TH-10D	90 x 20s = 30 min	89.2	47396.8	6.6	4245.9	10.3	235.7	15.5	-70.01	9.76	-10.36	14.80	3.68	23.69

AWCC — **With Cd liner, No Ni** — **8/22/2019** — *Note: ^{252}Cf in bottom plug, ^{232}Th on 7 cm stand in cavity*

Items	Measurement time	^{232}Th mass [g]	Singles	σ	Doubles	σ	Triples	σ	Δ Singles	σ	Δ Doubles	σ	Δ Triples	σ
FTC-CF-1992	120 x 20s = 40 min	0	34535.3	4.4	3309.4	6.2	185.5	7.6	-	-	-	-	-	-
FTC-CF-1992, TH-5D, TH-6D, TH-9D, TH-10D	120 x 20s = 40 min	89.2	34412.4	4.6	3291.0	6.8	181.5	8.3	-122.92	6.36	-18.36	9.17	-4	11.22

ENMC — **8/22/2019** — *Note: ^{252}Cf on rod, ^{232}Th on 7 cm stand in cavity*

Items	Measurement time	^{232}Th mass [g]	Singles	σ	Doubles	σ	Triples	σ	Δ Singles	σ	Δ Doubles	σ	Δ Triples	σ
FTC-CF-1992	120 x 20s = 40 min	0	229281.5	16.7	141382.3	49.4	50580	137	-	-	-	-	-	-
FTC-CF-1992, TH-5D, TH-6D, TH-9D, TH-10D	120 x 20s = 40 min	89.2	229235.2	17.6	141350.0	56.0	50593	148	-46.27	24.27	-32.29	74.66	12.605	201.31

AWCC — **With Cd liner, with Ni** — **7/30/2019** — *Note: AmLi in top plug, ^{232}Th on stand in cavity*

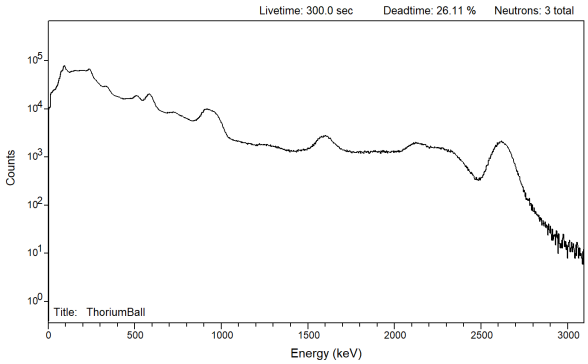
Items	Measurement time	^{232}Th mass [g]	Singles	σ	Doubles	σ	Triples	σ	Δ Singles	σ	Δ Doubles	σ	Δ Triples	σ
N-471	106 x 30s = 53 min	0	2341.53	0.87	1.15	0.32	0.24	0.10						
N-471, TH-10D	90 x 30s = 45 min	15	2346.06	0.90	0.73	0.34	0.38	0.11	4.53	1.25	-0.42	0.47	0.141	0.15

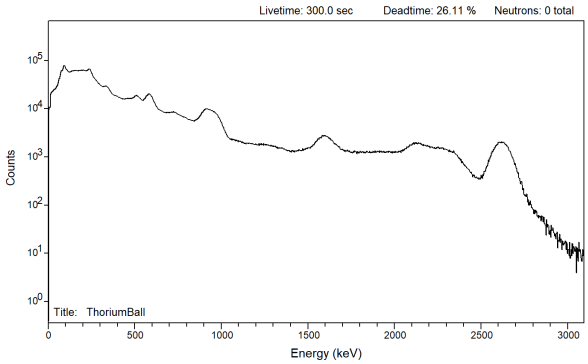
PASSIVE Measurements

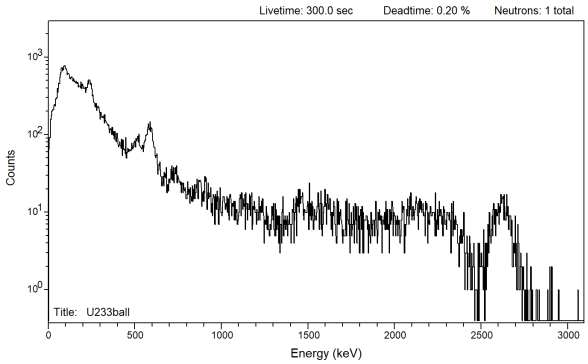
ENMC — **6/27/2019**

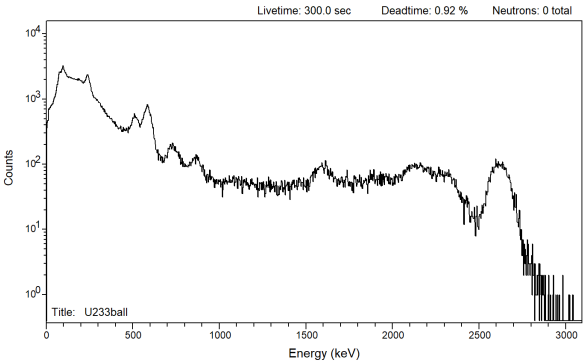
Items	Measurement time	^{232}Th mass [g]	Singles	σ	Doubles	σ	Triples	σ
NI-TH3KG		3000	1.68	0.58	1.67	0.89	3.3	2.2
TH-10D		15	0.29	0.48	0.53	0.18	0.68	0.33

Appendix D: Thorium.pcf, which also contains U233 output.

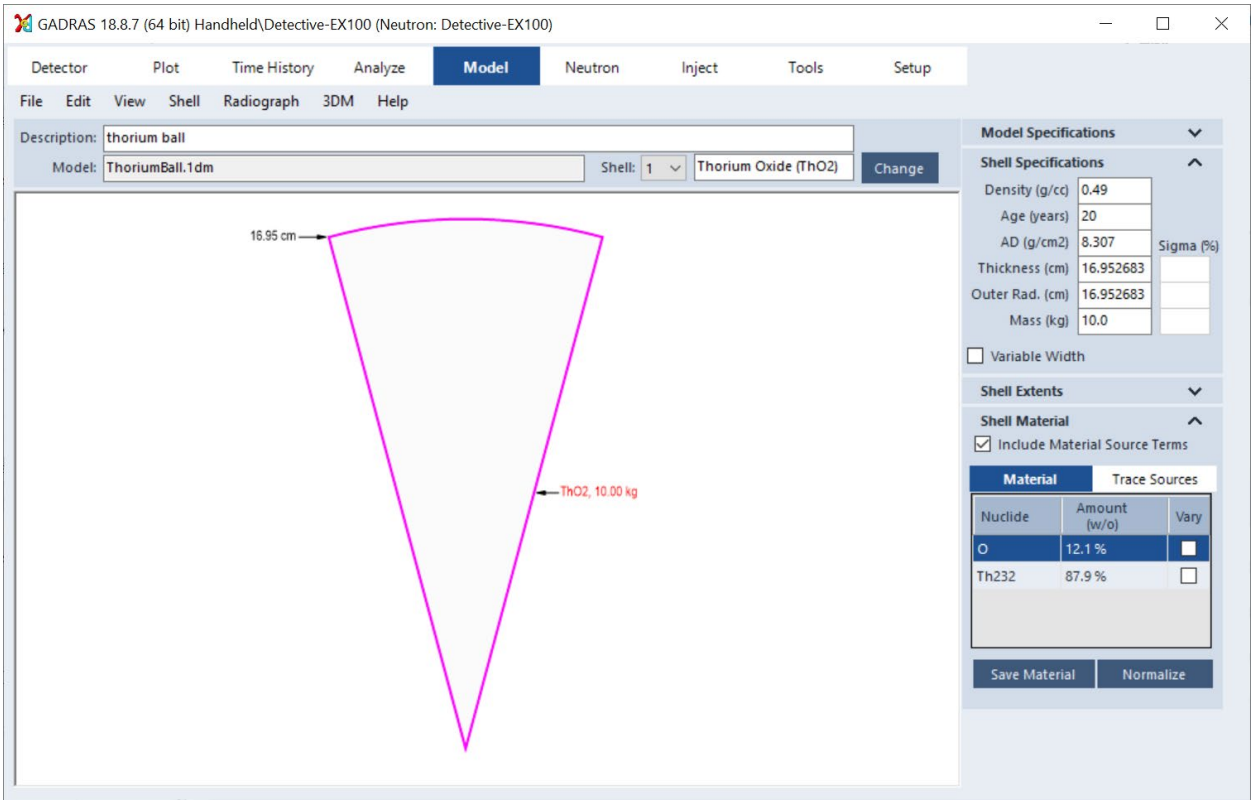


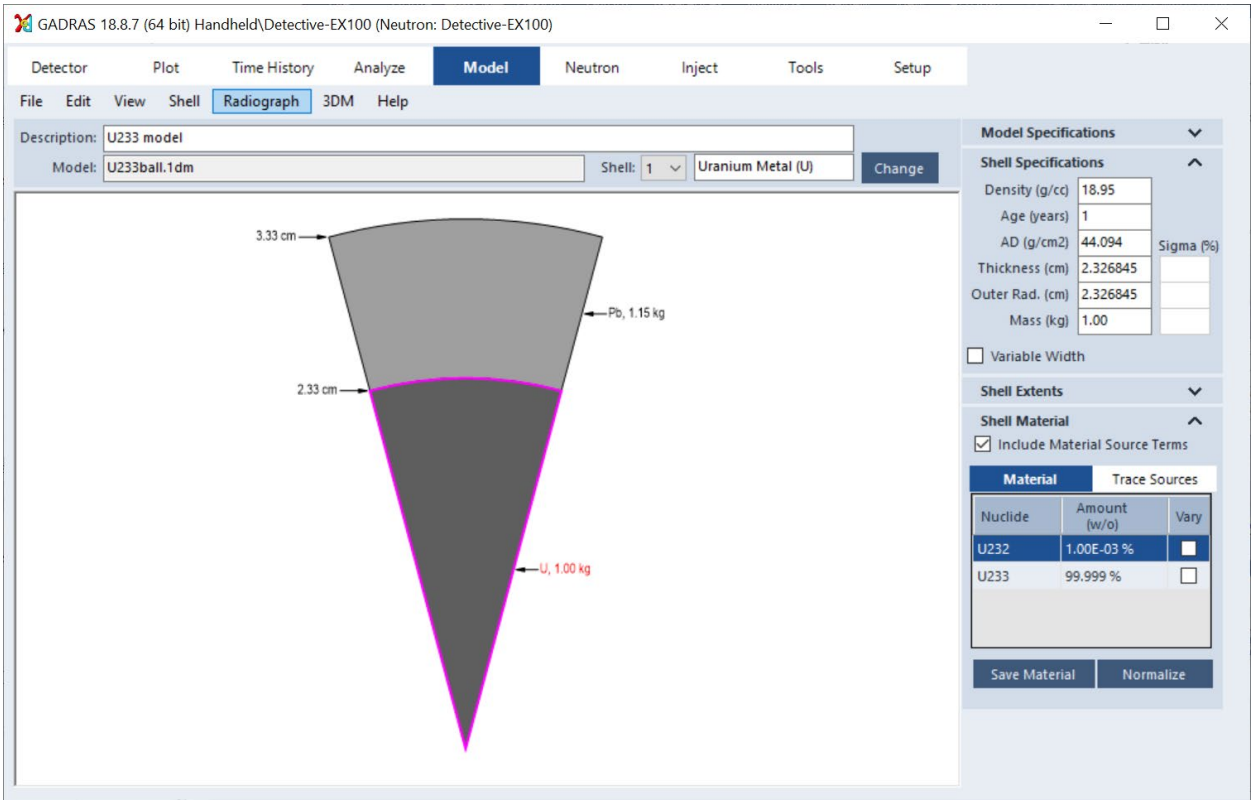




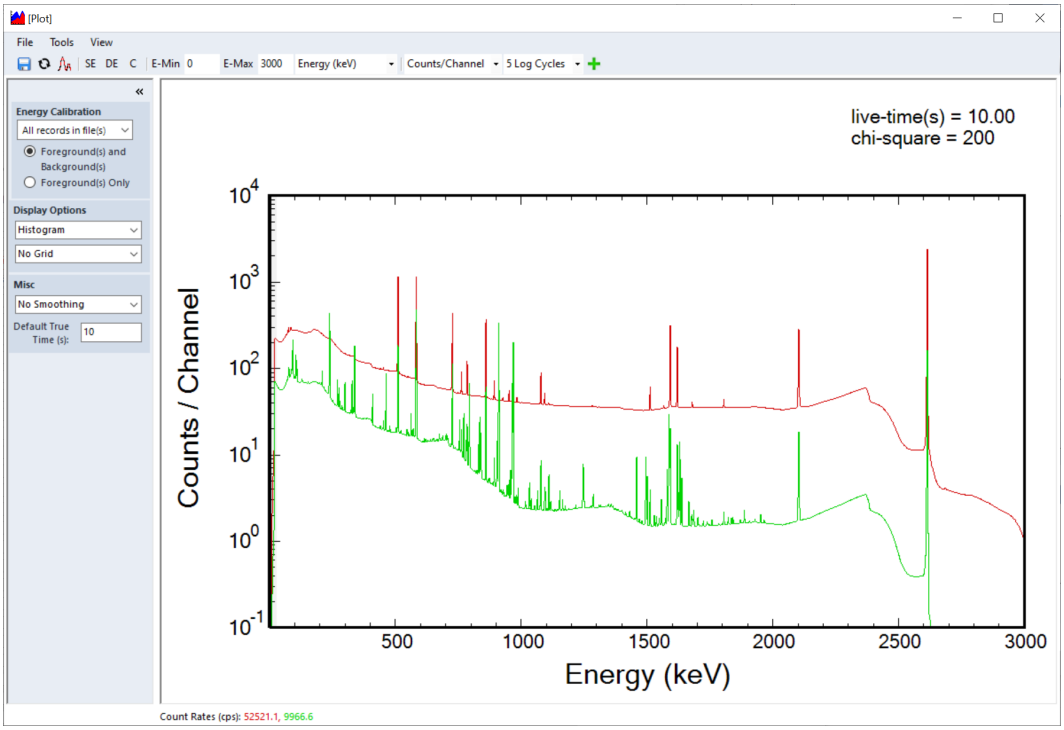


Appendix E: GADRAS Model Files





Appendix F: Gam file physics information. (U233=red, Thorium=green). For ease of viewing the information is plotted after folding with a Detective EX-100 function. File header and tail text are also shown below.




```
GamFileVersion = 2.1
DataType = SnTransport 18.8.10.0
Geometry = Spherical
Description = thorium ball
LargestDimension = 3.391E+01
Data =
        568          92         79 ! photon lines, photon groups,
neutron groups
…

0.00298824091441929 ! k-eff
1.00299719726191 ! multiplication


GamFileVersion = 2.1
DataType = SnTransport 18.8.10.0
Geometry = Spherical
Description = U233 model
LargestDimension = 6.654E+00
Data =
        334         144         79 ! photon lines, photon groups,
neutron groups
…

0.465361446142197 ! k-eff
1.87042253646745 ! multiplication
```